THE DECEMBER 1962 REPORT OF THE RBE COMMITTEE TO THE ICRP AND ICRU IN ITS IMPLICATIONS FOR THE ASSESSMENT OF PROTON RADIATION EXPOSURE IN SPACE

Hermann J. Schaefer

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Research Report

THE DECEMBER 1962 REPORT OF THE RBE COMMITTEE

TO THE ICRP AND ICRU IN ITS IMPLICATIONS FOR THE

ASSESSMENT OF PROTON RADIATION EXPOSURE IN SPACE

Hermann J. Schaefer

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Approved by

Captain Ashton Graybiel, MC USN
Director of Research

Released by

Captain Clifford P. Phoebus, MC USN
Commanding Officer

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SUMMARY PAGE

THE PROBLEM

The RBE Committee to the International Commission on Radiological Protection (ICRP) and the International Commission on Radiological Units and Measurements (ICRU) issued, in December 1962, an erudite study on the present state of knowledge concerning the Relative Biological Effectiveness (RBE), discussing established facts as well as those facets of the problem for which experimental evidence is missing or ambiguous. It seems of interest to investigate how earlier assessments of RBE doses from proton radiations in space stand up in the light of the new recommendations.

FINDINGS

The RBE Committee itself gives the fundamental answer in the statement: "There is no justification at the present time for departing from present ICRP practice, including the current relationship between RBE and Linear Energy Transfer (LET), restated above." Nevertheless, a more detailed discussion seems indicated for two particular propositions of the report. The first one concerns the distinction between RBE and Quality Factor (QF) and the formulae which are proposed for computing both factors for a given LET. Application of these formulae to the LET spectra of standard x-rays, flare produced protons, and neutron recoil protons leads, for the low LET section of the flare spectrum, to a slightly lower mean RBE than for standard x-rays. For the high LET section of the flare spectrum, it leads to a markedly higher RBE than for the neutron produced recoil proton spectrum. Because of the smallness of the fractional high LET dose in the flare spectrum, these traits do not show in the mean RBE and mean QF for this spectrum assessed as a whole. The total mean RBE of flare produced proton radiation is found to be 1.06 and the total mean QF 1.29.

The second recommendation of special interest concerns a more basic issue. The RBE Committee emphasizes the difference between low LET and high LET radiation for repeated or protracted low dose rate exposures with regard to accumulated residual injury. This strongly suggests that, for assessing a net lifetime dose or a net exposure status from repeated exposures over a more limited number of years, the two dose fractions be measured separately. For single exposures, such as one traversal of the Van Allen Belt or one encounter of a flare event, such separate measurement seems unnecessary as the acute damage, in this case, would be predominantly determined by the disproportionately larger ionization dosage of normal LET. However, as the aforementioned reasons call for a separate determination, dosimetric instrumentation for separate measurement would be needed anyhow.

INTRODUCTION

Accurate assessment of the exposure of man in proton radiation fields in space greatly depends upon the RBE factor for correct conversion from rad to rem doses. Experimental studies with protons from laboratory sources have shown that, in the energy range of several hundred Mev, an RBE well below 1.0 prevails (1, 2), whereas for neutron recoil protons whose energies center on 1.0 Mev, RBE values considerably larger than 1.0 have to be applied (3). In exposures to solar protons in space the local energy spectrum in tissue is a continuum extending from zero to many hundred Mev. In other words, it is a mixture of components of high and low RBE. Determination of a proper mean RBE for such a spectrum, therefore, requires separate assessment of these components. This can be accomplished by breaking down a given heterogeneous spectrum into narrow energy intervals, assigning to each of them the appropriate RBE factor, and reintegrating. The details of such an analysis have been described in earlier reports (4, 5).

Besides its scientific aspects, the RBE problem has also official implications, for instance, if the definition of maximum permissible exposure levels for radiation safety purposes or the appraisal of the exposure status of a person from repeated exposures is involved. In view of this multiplex significance of the RBE, it seems of considerable interest that the RBE Committee to the International Commission on Radiological Protection (ICRP) and International Commission on Radiological Units and Measurements (ICRU) issued, in December 1962, an extensive report (6) which summarizes the state of knowledge in experimental radiobiology concerning the RBE and arrives at more detailed recommendations concerning the dependence of RBE on Linear Energy Transfer (LET) than had been proposed before in the well-known Table 3 of Handbook 59 (7).

Since the earlier studies mentioned above have been based, in part, on the just-mentioned data in Handbook 59, it seems appropriate to examine the new report of the RBE Committee and to determine if and to what extent the earlier assessments of rem doses in solar proton beams would have to be revised. The following discourse is an attempt in this direction. It is limited strictly to this particular aspect and does not pretend to give a more general review of the RBE Committee's report. As indicated above, the report is quite comprehensive and renders a competent and detailed account of established facts as well as of those areas where experimental findings concerning the RBE are either incomplete or ambiguous. For these general aspects, the reader should consult the Committee report directly (6).

RELATIVE BIOLOGICAL EFFECTIVENESS (RBE) AND QUALITY FACTOR (QF)

It should be pointed out from the onset that the RBE Committee states, "There is no justification at the present time for departing from present ICRP practice, including the current relationship between RBE and Linear Energy Transfer

(LET), restated above." What is meant by the last phrase is the relationship set forth in Table 3 of Handbook 59. The earlier evaluations of rem doses from solar and Van Allen Belt protons mentioned above (4, 5) had been based on the upper contour of the RBE ranges proposed in the same Table 3 of Handbook 59. These values have also been adopted in the Life Sciences Data Handbook of NASA (8). Therefore, all these earlier recommendations retain full validity, and no revisions of earlier rem dose determinations are necessary.

The most important departure from established procedure, which the RBE Committee proposes, is the distinction between RBE and QF. It is well known that the RBE does not depend on LET only, but on numerous other parameters such as dose rate, fractionation, and total dose, not to mention the many biological factors. In defining official RBE values for given conditions in radiation safety practice, therefore, the worst possible combinations of influencing parameters have been assumed and the highest RBE values reported have been chosen, possibly even providing an additional safety margin. A radiobiological experimenter, on the other side, in reporting the findings of a particular experiment, will express RBE directly as the ratio of the corresponding rad doses of standard x-rays and of the radiation used in his experiment for equal biological effects. In view of these two basically different connotations, the RBE Committee proposes that for official matters the new term Quality Factor (QF) be used and that the term RBE be limited to denoting dose ratios actually observed in experimental work. For both magnitudes, RBE and QF, formulae are set forth in the report which allow a computation of them for any given LET. They read: $RBE = 0.9 + 0.05\ L$ and $QF = 0.8 + 0.16\ L$ where L is the LET to be expressed in units of kev/micron T. Use of the equation for QF is limited to a maximum LET of 100 kev/micron T. For protons, this restriction is immaterial since their maximum LET in the Bragg peak reaches only 91 kev/micron T.

Figure 1 shows RBE and QF computed by the indicated formulae for the entire LET interval of interest for protons. The shaded area in the graph indicates the range of RBE values as proposed in Table 3 of Handbook 59. It is seen that the QF curve very nearly coincides with the upper and the RBE curve with the lower contour of the earlier recommendations. The earlier assessment of rem/rad dose ratios for heterogeneous proton spectra, since they have been based on the upper contour, i.e., on the QF curve, therefore, remain fully valid with the only specification that the term RBE should be replaced by QF.

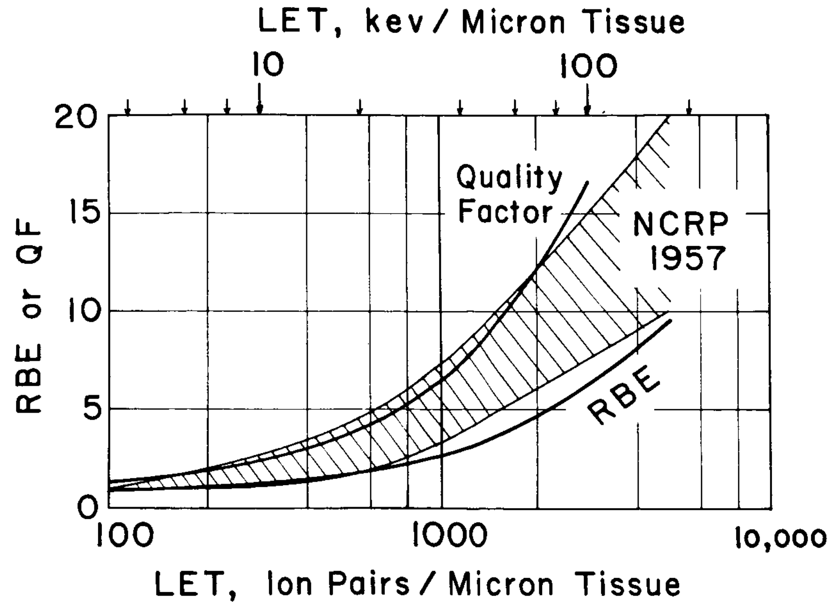

Figure 1

RBE and QF as a Function of LET According to Formulae Set Forth in 1962 Report of RBE Committee. Shaded area indicates 1957 recommendations.

EFFECT OF DOSE RATE ON RBE

As mentioned before, this treatise does not aspire to an analysis of all implications of the RBE Committee's report for proton radiations in space. Merely one more problem might be examined more closely since it bears directly on the assessment of the long range exposure status of an astronaut from repeated and protracted exposures to proton radiations. In paragraph 38 (6, p. 365), the report discusses the effect of dose rate on RBE and arrives at the conclusion "that the effectiveness of high LET radiation for life-shortening is relatively independent of dose rate whereas that of low LET radiations decreases with decreasing dose rate by a factor of at least 2-3 over the range of dose rates investigated." This statement indicates that, for exposures to heterogeneous radiations in which the total dose is administered partly by a low LET and partly by a high LET component, the two fractions should be determined separately since they show different cumulative net effects if long-term damage such as life shortening is to be assessed. This particular aspect has been discussed already in an earlier study (9). As its importance appears to be re-emphasized in the new document of the International Commissions, a more detailed analysis of the two dose fractions in question for a typical solar particle beam seems of interest.

TRANSITION OF THE ENERGY SPECTRUM OF A HETEROGENEOUS PROTON BEAM IN SHIELD OR TISSUE

The high LET fraction of the local ionization dosage of a heterogeneous proton radiation is produced exclusively by low energy protons. The LET of protons passes through a steep maximum of 91 kev/micron T at a residual range of 2 micra in tissue corresponding to a residual kinetic energy of 0.12 Mev. This means that the high LET dose is contributed exclusively by protons in the terminal sections of their paths, so-called "enders." In a given differential energy spectrum, then, the fractional flux at the low energy end of the spectrum determines the high LET dose. Fractional fluxes of higher energies will reach the critical energy level at which the LET becomes high at a point farther down-range in the direction of travel after the protons have been slowed down sufficiently. Because of the strongly nonlinear dependence of LET on kinetic energy, the differential particle number, i.e., the number of particles per unit energy interval, changes continuously during this transition, as will be analyzed presently in more detail.

In a differential energy spectrum, any individual ordinate value denotes a particle number per unit energy interval: $N_{diff_E} = dN/dE$. Furthermore, the LET of a particle of energy E denotes the energy dissipation per unit length of travel: $L = dE/dR$. It is seen, then, that multiplication of the two magnitudes furnishes the particle number $N_{diff_R} = dN/dR$ per unit range interval, i.e., the corresponding individual ordinate in the differential range spectrum. dN/dR has the great advantage over dN/dE in that it does not change with changing residual range R when the beam travels more deeply into absorbing material as long as particle elimination due to nuclear interactions is disregarded. The local energy dissipation at any depth, therefore, can be obtained directly by multiplying dN/dR by the corresponding LET. Furthermore, dN/dR can be reconverted, for any residual range R, into dN/dE simply by dividing it by the corresponding LET: $(dN/dR)/(dE/dR) = dN/dE$. Since the LET is maximal at the Bragg peak closely before the end of the track, it is seen that the differential particle number dN/dE at the Bragg peak, i.e., at near zero kinetic energy, must be smaller than at any higher kinetic energy.

Figures 2 and 3 give a detailed account of the just-described relationship for a concrete case. Figure 2 shows the differential energy spectrum of a typical flare produced solar particle beam. The spectrum shows consistently a pronounced negative slope; i.e., the particle flux decreases substantially toward higher energies. Only the middle section of the spectrum is shown, i.e., the section which would predominantly contribute to the tissue ionization dosage in a human target under exposure conditions in space. It might be said, however, that toward the right the spectrum continues to drop until it reaches the level of the proton component of the ordinary cosmic ray beam. Similarly, the particle flux continues to rise toward the left until a geomagnetic or instrument cutoff is reached, below which direct measurements are no longer possible. Indirect evidence from auroral phenomena associated with flare produced proton fluxes indicates that the increase extends all the way down to very low energies which are equivalent to thermodynamic particle velocities.

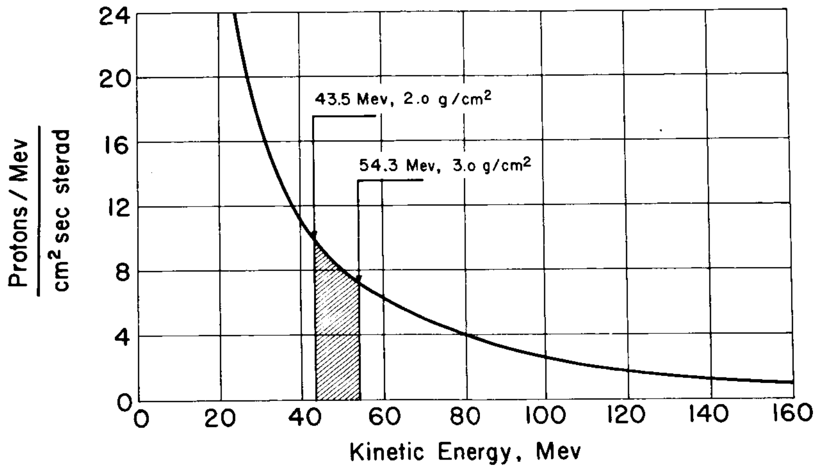

Figure 2

Differential Energy Spectrum of Incident Proton Beam From A Typical Flare Event

If we single out, in the spectrum of Figure 2, a narrow interval, e.g., from 43.5 to 54.3 Mev corresponding to a range interval in tissue from 2.0 to 3.0 g/cm^2, it is seen that, because of their slightly higher LET, the particles of lower energy in this interval will lose energy faster in a given thickness of absorbing material than those of higher energy at the upper end of the energy interval in question. The original energy spread of 54.3 minus 43.5 equals 10.8 Mev, therefore, must become larger as the radiation penetrates more deeply into the absorber. Since no new particles are generated, the particle number per Mev must decrease. This spreading of the selected partial flux in the incident beam over ever larger energy intervals is shown for consecutive steps of 0.4 g/cm^2 in Figure 3. As the energy interval expands, the spectral slope decreases continuously, becomes horizontal, and finally reverses, with the differential particle number dN/dE dropping continuously. This decrease of dN/dE progresses in an uneven fashion with the lower end of the energy interval affected most. In our particular case, dN/dE drops from 9.75 protons/Mev at 43.5 Mev to 0.20 protons/Mev at 0 Mev. The most conspicuous consequence of the transition of the differential particle number is the change of the monotonic negative slope of the incident spectrum into a configuration which shows a pronounced maximum at a finite energy.

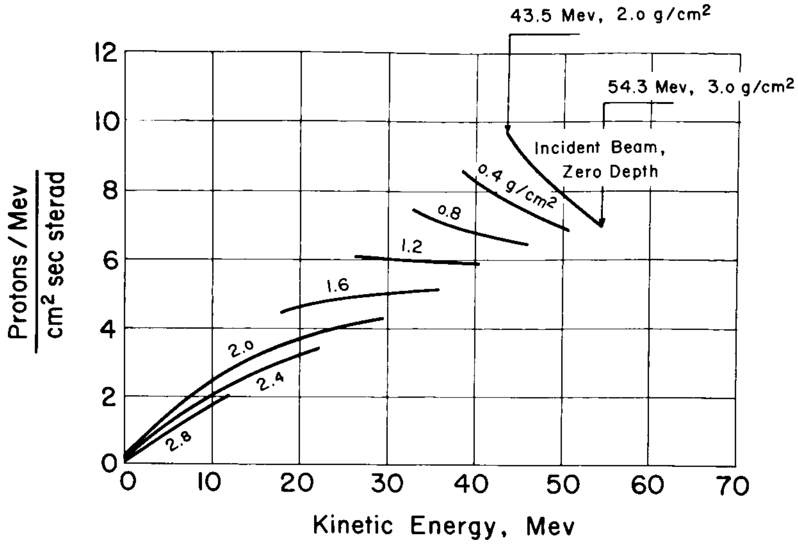

Figure 3

Transition of Spectral Section of Incident Beam Marked Off
In Figure 2 Toward Greater Depths in Organic Absorber

It should be noted that the particle number dN/dE at zero kinetic energy is not zero, but has a finite value which is representative of the number of "enders," i.e., of protons reaching the end of their ionization range. Since these are precisely the particles which produce the high LET fraction of the local dose, the differential particle number at zero kinetic energy is an important quantity in a complete dosimetric evaluation.

LOCAL LET SPECTRUM OF A HETEROGENEOUS PROTON BEAM IN SPACE

For assessing the high LET fraction of the local ionization dosage in tissue from a heterogeneous proton beam, a specific assumption has to be made as to the critical value beyond which the LET is considered "high." For a suitable choice of this value, the configuration of the differential LET spectrum has to be investigated. The details of how this spectrum can be established have been described in an earlier report (10). For the representative LET spectra derived there, no special provisions for a higher resolution in the critical region closely below and at the Bragg peak had been made since the energy dissipated in this region was found to represent only a few per cent of the total ionization dosage. In the present context, main emphasis rests on this particular dose fraction, because a high RBE and QF factor has to be applied to it. Therefore, the earlier computations have been reprogrammed, for this particular section, applying a scale of smaller LET intervals of varying size which ensures a better definition of the upper end of the LET spectrum.

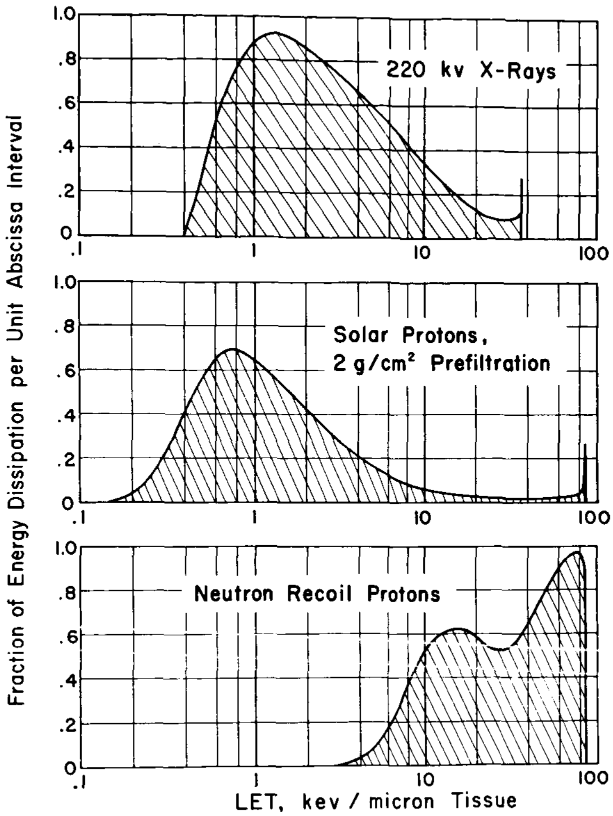

Figure 4

LET Spectra of Standard X-Rays, Flare Produced Protons, and Neutron Recoil Protons from Thermal Fission

Figure 4 shows the results of the new analysis to which so far only the flare produced spectrum for a tissue depth of 2 g/cm^2 and the spectrum of neutron produced recoil protons have been subjected. The upper graph of Figure 4 shows the LET spectrum for standard x-rays as computed by Cormack and Johns (11); the center graph pertains to the flare spectrum, and the lower one to recoil protons. Focusing the attention on the upper end of the spectra of standard x-rays and flare produced protons, one sees that, in addition to the broad main maximum, an extremely sharp second maximum exists at the upper end of the LET scale in both spectra. For standard x-rays this "spike" lies at 38 kev/micron T and for flare produced protons at 85 kev/micron T. One could argue, then, that the specifically different quantity in the flare produced spectrum, as compared to x-rays, would have to be sought in the dose contribution in the LET interval from 38 to 85 kev/micron T where x-rays do not show any energy dissipation. Actually, this statement describes only part of the difference between the two spectra inasmuch as also the respective particle track lengths, along which high LET values are maintained, have to be considered. These relationships have been discussed in the earlier study (10). In the present context it might suffice to point out that the much shorter track lengths over which electrons maintain an LET of, and beyond, 25 kev/micron T as compared to protons would call for a lowering of the critical LET limit below the above proposed value of 38 kev/micron T. In the following evaluation a value of 30 kev/micron T has been adopted as a conservative compromise.

Since the configuration of the energy spectrum of a heterogeneous proton beam changes continuously as the radiation penetrates more deeply into the absorber, the corresponding changes of the LET spectrum have to be analyzed. Figure 5 presents the pertinent information. It shows once more the LET spectrum of the center graph of

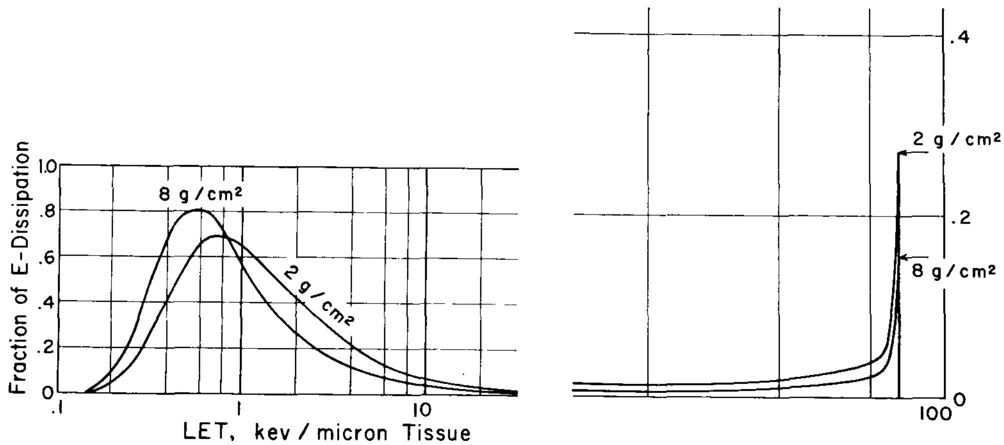

Figure 5

LET Spectrum of Flare Produced Protons for Two Prefiltration Thicknesses (Section from 30 to 100 kev/micron tissue is set off and drawn at larger scale for better readability.)

Figure 4 and in addition the corresponding spectrum after the beam has travelled through additional 6 g/cm^2 of tissue. The graph is dissected at 30 kev/micron T with the right-hand section drawn at a larger scale for better clarity. It is seen that the height of the maximum at 85 kev/micron T drops substantially as the beam proceeds from 2 to 8 g/cm^2 depth. Since RBE and QF are very high at 85 kev/micron T, this reduction of the maximum constitutes a much greater change of the dose equivalent (rem dose in old terminology) than would a similar reduction in the section of medium or low LET values.

MEAN RBE AND MEAN QF OF A HETEROGENEOUS PROTON BEAM IN TISSUE

The spectra of Figure 4 lend themselves easily to an evaluation in terms of dose equivalents according to the formulae of the RBE Committee for RBE and QF. This evaluation can be accomplished by multiplying the ordinates of the LET spectra by the corresponding RBE or QF, respectively, numerically integrating the fractional rem dose contributions and establishing the mean RBE and QF by dividing by the total ionization dose. In view of the special significance of the dose contribution in the LET interval from 30 to 85 kev/micron T, it seems indicated to carry out this analysis for the proton spectra (center and bottom graph in Figure 4) in two different ways, once for the whole LET spectrum and once with the sections below and above 30 kev/micron T treated separately.

Table I shows the results of the indicated evaluation. It is of special interest that for x-rays both the mean RBE and mean QF are higher than 1.0 and at the same time higher than the factors for the corresponding LET section of the flare spectrum. In other words, the configuration of the main maximum of the flare spectrum leads to a lower mean LET than the x-ray spectrum. This is due to the protons in the multi-million e-volt energy range which have been found, as mentioned in the Introduction, to have an RBE well below 1.0. If the flare spectrum is taken in its entirety, i.e., including the high LET section beyond the upper LET limit of the x-ray spectrum, the lower RBE is more than cancelled out by the substantially higher RBE and QF values of the high LET fraction.

Table I

RBE and QF Computed by the Formulae of the RBE Committee For the LET Spectra of Typical Radiations

Type of Radiation		RBE	QF
Standard X-Rays		1.11	1.46
Flare Produced	Low LET Fraction*	1.00	1.13
Protons at 2 g/cm^2	High LET Fraction	4.06	10.80
Depth	Total mean	1.06	1.29
Neutron Recoil	Low LET Fraction	1.75	3.51
Protons in	High LET Fraction	3.79	10.05
Tissue	Total mean	2.64	6.36

*LET below 30 kev/micron T is considered low; above, high.

It might be mentioned in passing that the experimentally established fact of an RBE well below 1.0 for monoenergetic protons of many hundred Mev is not reflected very well in the proposed formulae of the RBE Committee. Therefore, it does not seem advisable to attempt a more detailed analysis as to what extent the high LET contribution in the flare spectrum could be considered compensated by the low LET section for which the RBE is smaller than 1.0. Quite generally, such detailed balancing of fractional ionization dosages with RBE and QF factors larger and smaller than 1.0 is unrealistic and would overextend the meaning of the formulae in question.

Another interesting relationship in the data of Table I concerns the mean RBE and mean QF for the high LET section of the flare produced beam as compared to that of neutron recoil protons. Table I indicates that the factors for the flare spectrum are slightly higher than those for the neutron recoil spectrum. The reason for it is easily seen in Figure 4. The neutron recoil spectrum has a broad, bimodal maximum at the upper end of the LET scale reaching out much farther to the left than the narrow spike of the flare spectrum, i.e., carrying larger dose fractions at medium high LET values in the interval below 80 kev/micron T than the flare spectrum. This means that the high LET fraction of an exposure to flare protons, assessed separately, constitutes a higher dose equivalent (higher rem dose) than an equal ionization dose from neutron recoil protons.

CONCLUSIONS

In summarizing the results of the foregoing discussion it can be said that the new recommendations of the RBE Committee to the ICRP and ICRU do not change the existing assessments of dose equivalents for proton radiations in space. They merely place those earlier assessments on a firmer basis by linking RBE and QF with exact formulae to LET. With regard to the Committee's recommendation to distinguish the RBE to be used for determining rem doses in scientific work from the QF to be used in official radiation safety matters, the question remains open how it would apply to manned space operations. Conceivably, QF dose equivalents could be used for defining maximum permissible levels in general whereas RBE dose equivalents could be resorted to in actual emergencies when impending acute radiation damage is to be assessed as closely as possible.

Important implications of the new document derive from its re-emphasizing the basic radiobiological difference between high LET and low LET radiation as far as low dose rate, long-term damage is concerned. This emphasis strongly suggests that, for exposures to ionizing radiation in space in general and to solar particle beams in particular, a separate measurement of the normal LET and the high LET fraction of the total dose is advisable. As a limiting value between the two types of exposures, the LET of 30 kev/micron T could be tentatively adopted. In view of the smallness of the high LET fraction of exposures to ordinary large flare events the separate measurement would seem dispensable for a single acute exposure. However, assessment of lifetime doses or even of accumulated net injury from repeated exposures over more extended time periods would require separate measurements. It would seem, therefore, that appropriate instrumentation has to be developed in any case. Several avenues exist along which such dosimeters could be designed. Simulating mixed radiation beams in the laboratory containing a large fraction of normal LET radiation such as x-rays and a smaller fraction of high LET radiation such as low energy protons should pose no serious problem. The indicated instrumentation, therefore, can be developed on the ground with costly testing in actual space flight limited to the final prototype.

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